Technical Report

Award Number: 02HQGR0048

HYBRID WAVE PROPAGATION MODELING BASED ON 1D DISCRETE-WAVE NUMBER AND 3DFINITE-DIFFERENCE METHODS

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Research supported by the U.S. Geological Survey (USGS) Department of the Interior, under USGS award number 02HQGR0048. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Abstract

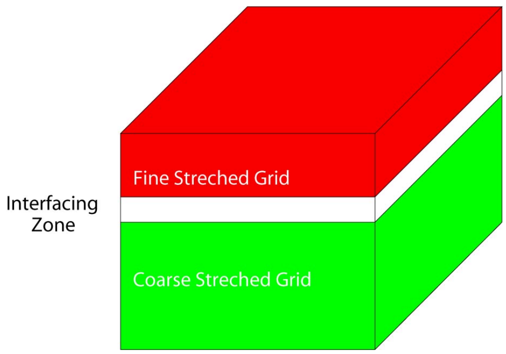
To realize accurate representation of large-scale sedimentary basin structures in the long-period ground motion modeling of large earthquakes using finite-difference method, we propose a technique that combines the discontinuous grid and variable grid spacing approaches. Our intention is to develop a technique capable of treating 3D heterogeneous structures using highly optimized 3D-FD methods. We have developed an efficient simulation technique that can be used to model ground motion down to 1 s period in large-scale basin structures with minimum shear-wave velocity of 300 m/s. The technique is also suitable for treating distant and deep earthquakes, including subduction zone earthquakes.

Results

Ground motion modeling in sedimentary basins requires numerical techniques that have the capability of treating realistic geological structures. However, most of the numerical techniques commonly used in wave propagation modeling are usually restricted to particular aspects of the wave field or limited frequency range (Takenaka et al., 1998). In such conditions and for distant earthquakes it is advantageous to use the so-called "hybrid approach" which combines different numerical methods. The hybrid methods offer advantages not provided by a single method on its own (e.g. Alekseev and Mikhailenko, 1980; Ohtsuki and Harumi, 1983; Kummer et al., 1987; Fah, 1992; Bouchon and Coutant, 1994; Moczo et al., 1997; Wen and Helmberger, 1997). Most of the hybrid techniques that are used in ground motion modeling combine finite-difference and finite-element methods with 1D analytical or numerical methods, and point sources (e.g. Frankel and Vidale, 1992; Graves, 1994; Fah et al., 1994; Zahradnik and Moczo, 1996). Due to computational demands of the techniques involved, such schemes have been restricted to point sources and mainly 2D wave propagation modeling. For example, in a simulation of ground motion in Santa Clara valley from a Loma Prieta earthquake aftershock, Frankel and Vidale (1992) used an analytical representation of the input wave field that was used to excite one of the faces of the 3D grid. A more elaborated scheme that involved combinations of 3D FD simulations for calculating the external and internal 3D wave fields was used by Olsen et al. (2000) to simulate wave propagation in Borrego valley from a distant point source. During our attempt to extend such technique to large-scale 3D heterogeneous structures using conventional machines we encountered several obstacles that were mainly caused by the extensive disk space and i/o requirement of the scheme.

Instead here we used a new approach to 3D wave propagation modeling by combining an optimized variable grid 3D FD scheme (Pitarka, 1999), and discontinuous grid scheme of (Aoi and Fujiwara, 1999). The proposed scheme combines refined stretched grid inside the basins and sparse grid outside it, in the surrounding rock.

From the algorithmic point of view the key procedure of the hybrid schemes is the interfacing of wave propagation between the two grids along a particular plane (Figure 1). The interfacing has been successfully implemented in 3D FD schemes with constant grid spacing (e.g. Aoi and Fujiwara, 1999). Similar algorithms can be extended to the case of 3D-FD methods in which the interfacing is realized along selected planes that define the boundary between the two different grids. The new developments in the 3D hybrid schemes need to be focused on the techniques that reduce the number of grid points at the interface as well as in areas of high velocity. The staggered-grid FD schemes with varying grid spacing and discontinuous grids have such capabilities.



The main drawback of the Aoi and Fujiwara (1999) technique is that it is designed for 2-nd order FD operators, and thus, requires a finer spatial sampling, compared to 4-th order FD operators. This limitation increases substantially computational requirements and makes the 3D modeling impractical. Nevertheless their algorithm is straightforward and applicable to higher order FD operators. In our scheme we use 4-th order FD operators with variable spacing.

Figure 1. Discontinuous grid layout

Interfacing Methodology

Our interfacing scheme is flexible since it allows for variable grid spacing in both grids, and variable grid spacing increments at the interface zone as well. The basic idea of the interfacing algorithm is to make the boundary between the two grids transparent by interpolating the wavefield calculated in each grid in the interface region. Because the grids are staggered the interfacing involves interpolations of velocity and stress along planes within the interfacing region. A schematic view of the 3D interfacing as viewed along a vertical 2D cross section, normal to the Y-axis, is shown in Figure 2. Both upper and lower regions have variable spacing in all three directions. The horizontal grid spacing in the lower regions is factor of three smaller than that in the upper region. In the staggered grid schemes changing the grid spacing by odd factors guaranties that the coarse grid will align exactly with the fine grid at the interface nodes. . Within each region standard 4-th order FD operators are applied. For each time step the interfacing of wavefield parameters is performed in two steps. In step 1, the values of τ_{zz}, V_x, and V_y are computed at points of the finer (upper) grid located on the interface plane by interpolating between the corresponding wavefield parameters available at the nearest four coarse grid points.

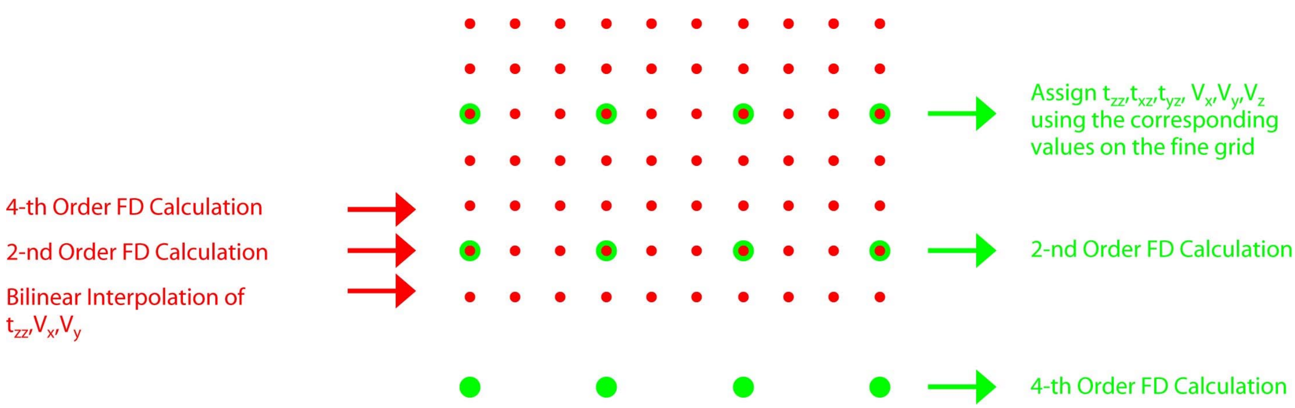


Figure2. Schematic view of the interfacing zone on a vertical plane crossing the fine grid (red dots) and coarse grid (green dots) regions of the 3D grid.

The interpolations are performed using a bilinear interpolation scheme. This scheme is much faster and requires less memory than an alternative 2D Fourier transform scheme. We tested its accuracy by comparisons against the 2D Fourier transform method for various complex surfaces. The linear interpolation scheme gave satisfactory results. In step 2, the sparse grid wavefield values of τ_{zz}, τ_{xz}, τ_{yz}, V_x, V_y, and V_z at grid points on the plane above the interface plane are exactly obtained using the corresponding wavefield parameters calculated in the upper grid. This sequence is repeated for all time steps. Unlike the technique of Aoi and Fujiwara (1999), in which the grid spacing increment factor at the interface is 3, in our approach this factor can be an odd number equal or larger than 3. A combination of Clayton and Enquist (19), and sponge zone absorbing schemes is applied in both grids in order to absorb the artificial reflections at the boundaries of the model. The width of the sponge zone is the same at both upper and lower grids.

Numerical Tests and Validation of the Technique

Based on the technique above we developed a computer program that calculates elastic wave propagation in heterogeneous structures using discontinuous grids with variable spacing. The proposed method was tested against the staggered grid FDM with variable spacing (Pitarka, 1999). In our tests we computed velocity seismograms in a linear station array from a double couple point source with an arbitrary focal mechanism, and located at a depth of 5.5 km. The first test was design to check the accuracy of the interfacing scheme therefore the velocity model was made homogeneous and elastic with Vp=5.2 km/s, Vs=3.0km/s, density =2.0 g/cm^3. For the 3D FD simulation, we use a model space 30 km wide, 20 km long and 10 km deep. The grid is continuous in the vertical direction, but its spacing changes from 100m to 300m at a depth of 4 km. In both horizontal directions the grid is discontinuous at 3.4 km depth where the horizontal grid spacing jump from 100m to 300 m. Compared with the grid with constant grid spacing, and for the same level of accuracy the grid used in this test reduces the computer memory requirement by at least a factor of 3. The grid also allows for accurate wave propagation modeling up to 2 Hz. In the second test we used a simple 3D basin velocity model. A cross section of the basin structure along the stations array is depicted in Figure 3. The basin velocity model is described in Table 1. In order to check the stability of our interfacing scheme in the case when the interface between the two grids crosses a medium with different seismic properties, the interface plane was placed across the basin at a depth of 1.4 km.

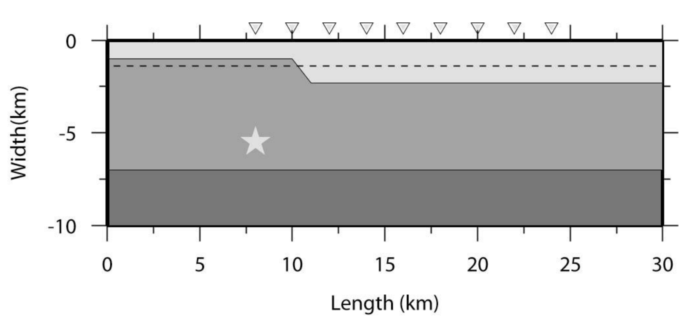


Figure 3. Cross-section of the 3D velocity model along the station array . Triangles show the stations location, and star shows the hypocenter location. Dotted line indicates the boundary where the grid is discontinuous.

Because a part of the basin area is covered by the sparse grid, the wave propagation modeling in the second test is accurate up to 0.6 Hz. Figure 4 shows the results of the first test. In this figure we compare the velocity seismograms calculated with the two techniques, band-pass filtered at 0.02-2. Hz. The results of the second test are shown in Figure 5. The synthetic velocity seismograms obtained with both techniques are band-pass filtered at 0.02-0.6 Hz. The good comparison between the two techniques in both tests demonstrates that the proposed FD method produces results with same level of accuracy as the classical staggered grid scheme. Other tests of the computer program not reported here showed that the interpolation scheme is stable even for heterogeneous models with strong material property contrast.

Using a new 3D-FD formulation based on discontinuous grids with variable spacing described in this report we can dramatically extend the bandwidth of the 3D-FD calculations, while, at the same time, decrease the minimum shear velocity requirement. This type of grid allows for refinement of the grid spacing in the basin region only, making possible the incorporation of more detailed structure that can be utilized to improve the fit to the recorded motions.

Table 1. Basin Velocity Model

Layer	**Vp(km/s)**	**Vs(km/s)**	**Density(g/cm^3)**	**Q**
Basin Sediments	2.2	1.0	1.7	30
Rock	4.2	2.0	1.8	100
Basement	5.2	3.0	2.0	1000

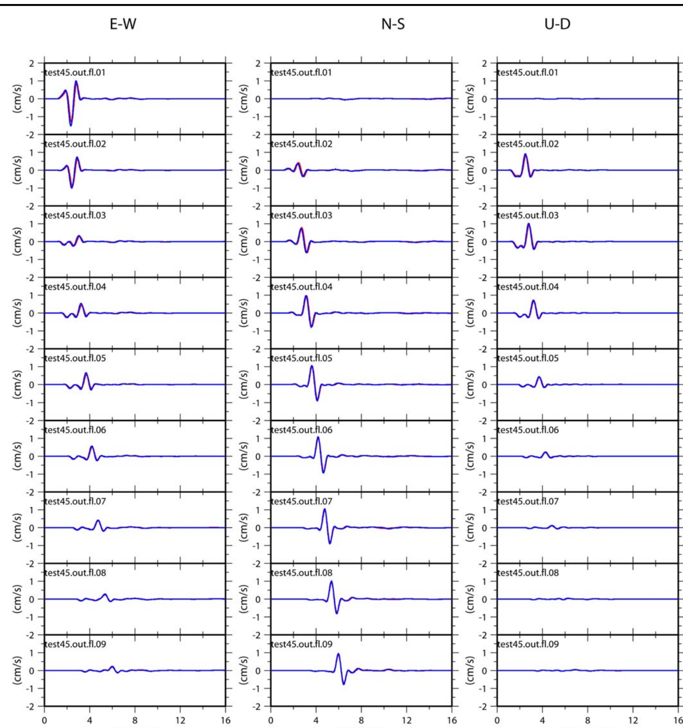


Figure 4. Comparison of point source velocity seismograms calculated with the proposed discontinuous grid scheme (blue traces) and the continuous grid scheme (red traces), using a half space velocity model.

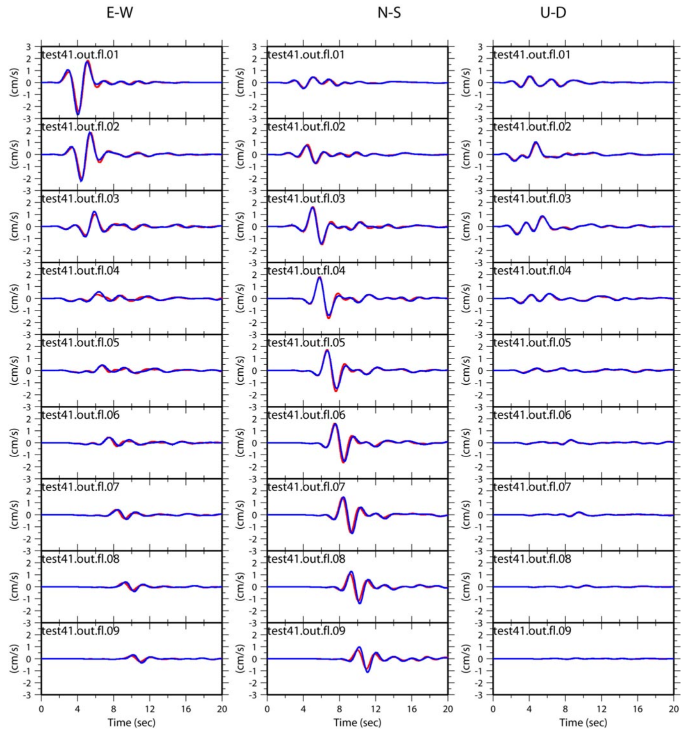


Figure 5. Comparison of point source velocity seismograms calculated with the proposed discontinuous grid scheme (blue traces) and the continuous grid scheme (red traces), using a 3D basin structure velocity model.

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